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ISO 9002 CERTIFIED

July 8, 1997

Mr. Cris Anderson
Director of Environmental Affairs
M.A. Hanna Company
200 Public Square, Suite 36-5000
Cleveland, Ohio 44114-2304

06720-023-001-0002

Re: Product Volume Calculation
L. E. Carpenter Site

Dear Cris:

Attached is the Product Volume Calculation for the above referenced site. Based on this calculation, the volume of recoverable product at the site is estimated to be 1,500 gallons to 5,900 gallons. This estimate was calculated using the August 1995 product bail-down test data, evaluated according to the method presented in *Determining Realistic Time Frames For Free Hydrocarbon Recovery by Michael T. Paczkowski and Stephen M. Testa*. Copies of the bail-down test data and the above referenced paper are attached.

As analytical data associated with soil porosity and product specific yield have not been collected, estimates for these parameters were used based on literature data. Therefore, the above estimate is considered to be preliminary, and the actual volume may vary. If required, we can calculate a more accurate volume by collecting soil porosity analytical data and product density and viscosity analytical data. The estimated cost to collect and analyze three soil and product samples for the above referenced parameters is estimated to be $3,000.

This information would be used to refine the estimates of product quantities. However, the rate of recovery will be governed by many other factors including product thickness distribution and hydrogeologic inhomogeneities, which cannot be calculated, and which can be significant especially when dealing with small thickness of product saturated soil.

It should be noted that the above estimate differs from the previous estimate of 2,000 gallons as reported in Section 3.5 - Estimate of Recoverable Product (page 3-3) in the *Third Quarter 1995 Progress Report, L.E.Carpenter Site, Wharton, New Jersey* dated October 1995. As discussed, no supporting calculations for the 2,000 gallon estimate could be found. Therefore, the estimated volume of recoverable product was recalculated.

If you should have any questions or require additional information, please feel free to contact me at 908-417-5800.

Very truly yours,

ROY F. WESTON, INC.

Thomas S Laudicina AT

Thomas S. Laudicina
Project Manager

cc: J. VanNordwick, RMT
M. Skirka, WESTON
B. McClellan, WESTON

L.E. CARPENTER SITE
WHARTON, NEW JERSEY

PRODUCT VOLUME CALCULATION

An estimate of the volume of recoverable product was calculated based upon the "true" product thickness calculated from product baildown tests in August 1995. The square footage of the product plume was determined using the product footprint from the 8 April 1997 monitoring event. The square footage was then multiplied by the "true" product thickness to determine the volume of product.

A. "True" product thickness based on inflection point of product baildown testing graphs (attached) generated using the August 1995 data.

MW-1R	0.90
MW-11S	0.90
WP-A6	0.17
WP-A7	0.30
WP-A8	0.02
WP-B3	0.06
WP-B4	0.50
WP-B5	0.01

B. Volume of Floating Product

To determine the volume of floating product at the site, the square footage of product was calculated using the "footprint" depicting the extent of product at the site (see attached figure). The plume has two areas elliptical in shape, where the product thickness is greater than the rest of the plume, one near MW-1R and the other near well MW-11S. In order to avoid overestimating the volume of product, the square footage was calculated separately for each of the elliptical areas and the remainder of the product plume separately, using the true product thickness for each area as follows.

1. The square footage of product was determined for each of the two ellipses:

MW-1R ellipse: (3.14159)ab   a = 25 ft.   b = 25 ft.

(25)(25)(3.14159) = 1,963 sq. ft.

MW-11S ellipse: (3.14159)ab   a = 55 ft.   b = 70 ft.

(55)(70)(3.14159) = 12,095 sq. ft.

PRODUCT VOLUME CALCULATION con't

2. The square footage for the entire footprint = 82,400 sq. ft. (Based on aerial extent of product plume as measured on 8 April 1997).

3. The area of the ellipses was subtracted from the total area:

   82,400 - 1,963 - 12,095 = 68,342 sq. ft.

4. The volume of product containing soil was calculated for each of the ellipses and for the surrounding area by multiplying the area by the true product thickness obtained from the baildown tests.:

   a. Volume of MW-1R ellipse:

      Product thickness = 0.90 foot (MW- 1R)

      1,963 sq. ft.(0.90 ft.) = 1,777 cubic feet (c.f.)

   b. Volume of MW-11S ellipse:

      Product thickness = 0.70 foot (average of the true thickness determined from WP-B4 and MW-11S)

      12,095 sq. ft. (0.70 ft) = 8,467 c.f.

   c. Volume of surrounding area:

      Product thickness = 0.14 foot (average of the true thickness determined from WP-B3, WP-A6, WP-A7, and WP-A8)

      68,342 sq. ft. (0.14 ft) = 9,568 c.f.

   d. Volume of floating product containing soil:

      1,777 c.f. + 8,467 c.f. + 9,568 c.f. = 19,812 c.f.

L.E. CARPENTER SITE
WHARTON, NEW JERSEY

PRODUCT VOLUME CALCULATION con't

C. Volume of Product

Product occurs in the soil pore space. Based on the types of soils present at the site (mixture of sands, silts, and clays) a 20% porosity is assumed.

19,812 c.f. soil (20% porosity) = 3,962.4 c.f. of product (7.48 gallons/c.f.)
~29,640 gallons

D. Volume of Recoverable Product

The actual rate of recovery is determined by the properties of the free product (such as viscosity), the product thickness, and the properties of the formation (porosity, moisture content). When the product thickness is small, the viscosity is high, and the soil moisture content is high, low percentages of product will be recovered. When the viscosity is low (high mobility), the product thickness is large (high head), the formation is porous and low in fines, and the moisture content is low, higher quantities of free product can be expected to be recovered.

Since site conditions at the site are expected to be a combination of the previously listed factors, and limited information is available, a range of recoverable product volume has been calculated based on recovery rates generally quoted in the literature (5% to 60%).

Lower end estimate: 29,640 gal. (0.05) = 1,482 gal.

Upper end estimate: 29,640 gal (0.60) = 17,784 gal.

The "common" recovery rate of 20% to 30% as quoted in the literature may be a realistic estimate.

20% recovery estimate: 29,640 gal. (0.20) = 5,928 gal.

60% recovery estimate: 29,640 gal. (0.30) = 8,892 gal.

Note:

An estimated 409 gallons of product has been recovered to date (Jan. 1995 to April 1997).

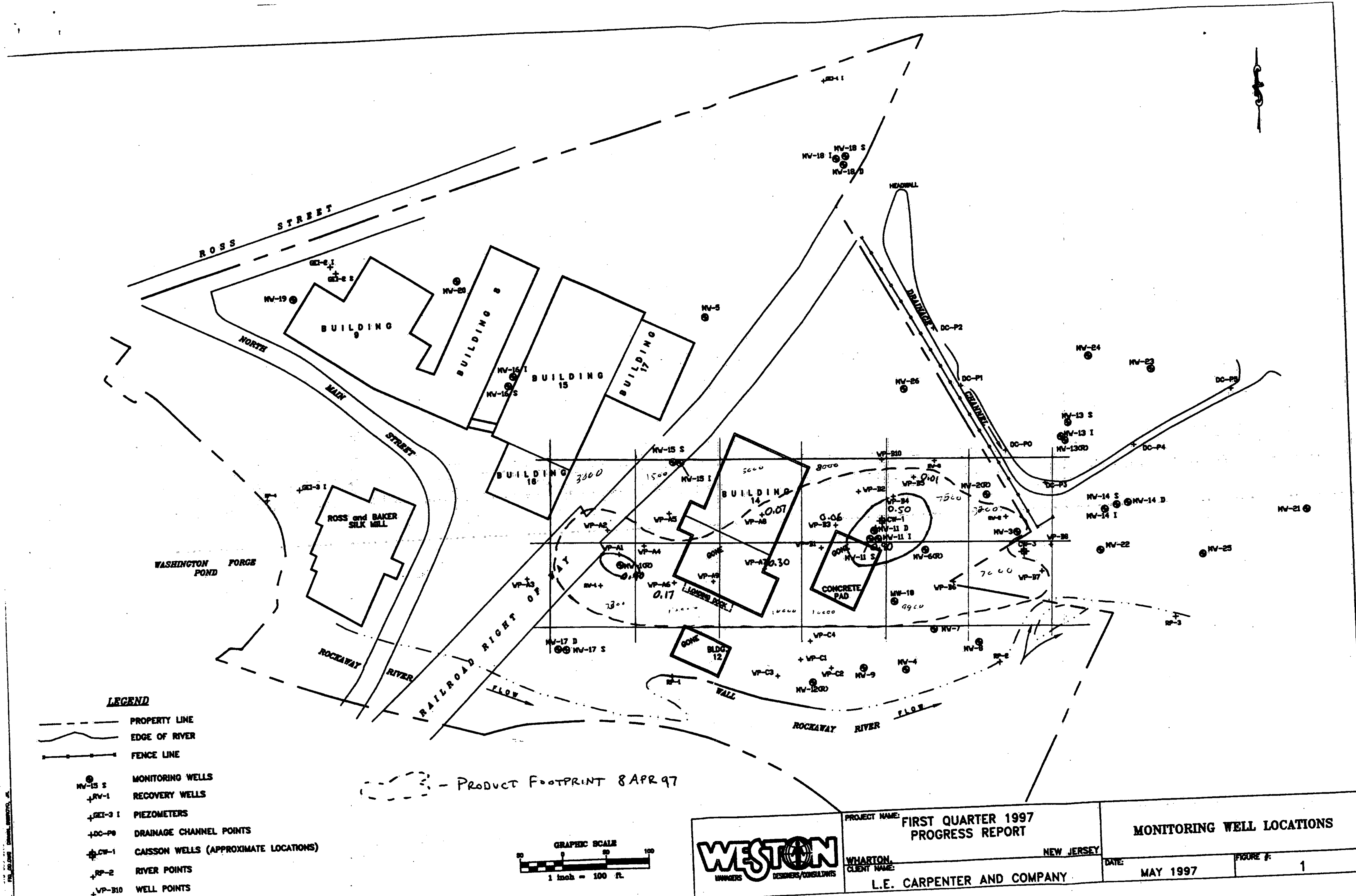
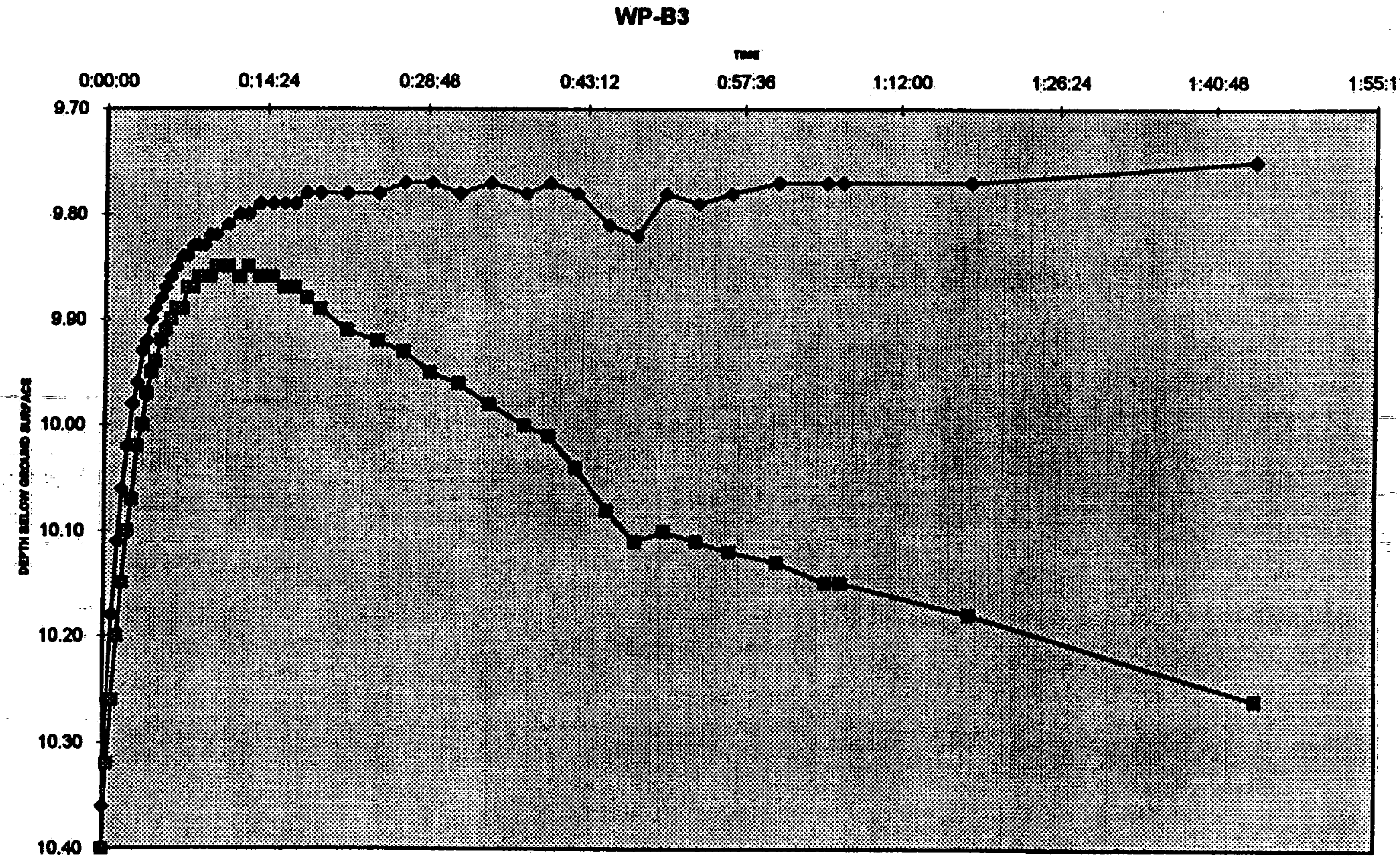

ROSS STREET
NORTH MAIN STREET
BUILDING 9
BUILDING 8
BUILDING 15
BUILDING 17
BUILDING 16
BUILDING 14
BLDG 12
ROSS and BAKER SILK MILL
WASHINGTON FORGE POND
RAILROAD RIGHT OF WAY
ROCKAWAY RIVER
FLOW
WALL
DRAINAGE CHANNEL
HEADWALL
CONCRETE PAD
LOADING DOCK
GONE
MW-19
MW-20
MW-5
MW-16 I
MW-16 S
MW-18 S
MW-18 I
MW-18 D
MW-15 S
MW-15 I
MW-26
MW-24
MW-23
MW-13 S
MW-13 I
MW-13(D)
MW-14 S
MW-14 D
MW-14 I
MW-21
MW-22
MW-25
MW-2(D)
MW-3
MW-11 D
MW-11 I
MW-11 S
MW-6(D)
MW-10
MW-7
MW-8
MW-4
MW-9
MW-12(D)
MW-17 D
MW-17 S
MW-1(D)
CW-1
CW-3
GEI-2 I
GEI-2 S
GEI-3 I
GEI-1 I
DC-P2
DC-P1
DC-P0
DC-P3
DC-P4
DC-P5
RP-1
RP-2
RP-3
VP-A1
VP-A2
VP-A3
VP-A4
VP-A5
VP-A6
VP-A7
VP-A8
VP-A9
VP-B1
VP-B2
VP-B3
VP-B4
VP-B6
VP-B7
VP-B8
VP-B10
VP-C1
VP-C2
VP-C3
VP-C4
0.50
0.30
0.17
0.07
0.01
0.40
G.06
3300
1500
5000
8000
7500
7200
7000
4900
LEGEND
PROPERTY LINE
EDGE OF RIVER
FENCE LINE
MW-15 S MONITORING WELLS
RW-1 RECOVERY WELLS
GEI-3 I PIEZOMETERS
DC-P0 DRAINAGE CHANNEL POINTS
CW-1 CAISSON WELLS (APPROXIMATE LOCATIONS)
RP-2 RIVER POINTS
VP-B10 WELL POINTS
- PRODUCT FOOTPRINT 8 APR 97
GRAPHIC SCALE
1 inch = 100 ft.
WESTON
MANAGERS DESIGNERS/CONSULTANTS
PROJECT NAME: FIRST QUARTER 1997 PROGRESS REPORT
WHARTON, NEW JERSEY
CLIENT NAME: L.E. CARPENTER AND COMPANY
MONITORING WELL LOCATIONS
DATE: MAY 1997
FIGURE #: 1

TABLE 4		
Bail-Down Test Performed At WP-B3		
Specific Gravity = 0.94		
ELLAPSED TIME	DEPTH TO PRODUCT (FEET)	DEPTH TO WATER (FEET)
0:00:00	10.36	10.40
0:00:22	10.26	10.32
0:00:45	10.18	10.26
0:01:12	10.11	10.20
0:01:35	10.06	10.15
0:02:03	10.02	10.10
0:02:29	9.98	10.07
0:02:56	9.96	10.02
0:03:21	9.93	10.00
0:03:43	9.92	9.97
0:04:07	9.90	9.95
0:04:29	9.89	9.94
0:05:00	9.88	9.92
0:05:26	9.87	9.91
0:05:54	9.86	9.90
0:06:24	9.85	9.89
0:06:57	9.84	9.89
0:07:24	9.84	9.87
0:07:54	9.83	9.87
0:08:22	9.83	9.86
0:08:58	9.83	9.86
0:09:27	9.82	9.86
0:09:58	9.82	9.85
0:10:59	9.81	9.85
0:12:00	9.80	9.86
0:12:47	9.80	9.85
0:13:50	9.79	9.86
0:14:54	9.79	9.86
0:15:59	9.79	9.87
0:16:56	9.79	9.87
0:18:01	9.78	9.88
0:19:16	9.78	9.89
0:21:41	9.78	9.91
0:24:23	9.78	9.92
0:26:45	9.77	9.93
0:29:09	9.77	9.95
0:31:40	9.78	9.96
0:34:26	9.77	9.98
0:37:33	9.78	10.00
0:39:43	9.77	10.01
0:42:16	9.78	10.04
0:45:13	9.81	10.08
0:47:46	9.82	10.11
0:50:23	9.78	10.10

TABLE 4		
Bail-Down Test Performed At WP-B3		
Specific Gravity = 0.94		
ELLAPSED TIME	DEPTH TO PRODUCT (FEET)	DEPTH TO WATER (FEET)
0:53:20	9.79	10.11
0:56:25	9.78	10.12
1:00:51	9.77	10.13
1:05:18	9.77	10.15
1:06:44	9.77	10.15
1:18:25	9.77	10.18
1:44:23	9.75	10.26
2:01:08	9.76	10.30

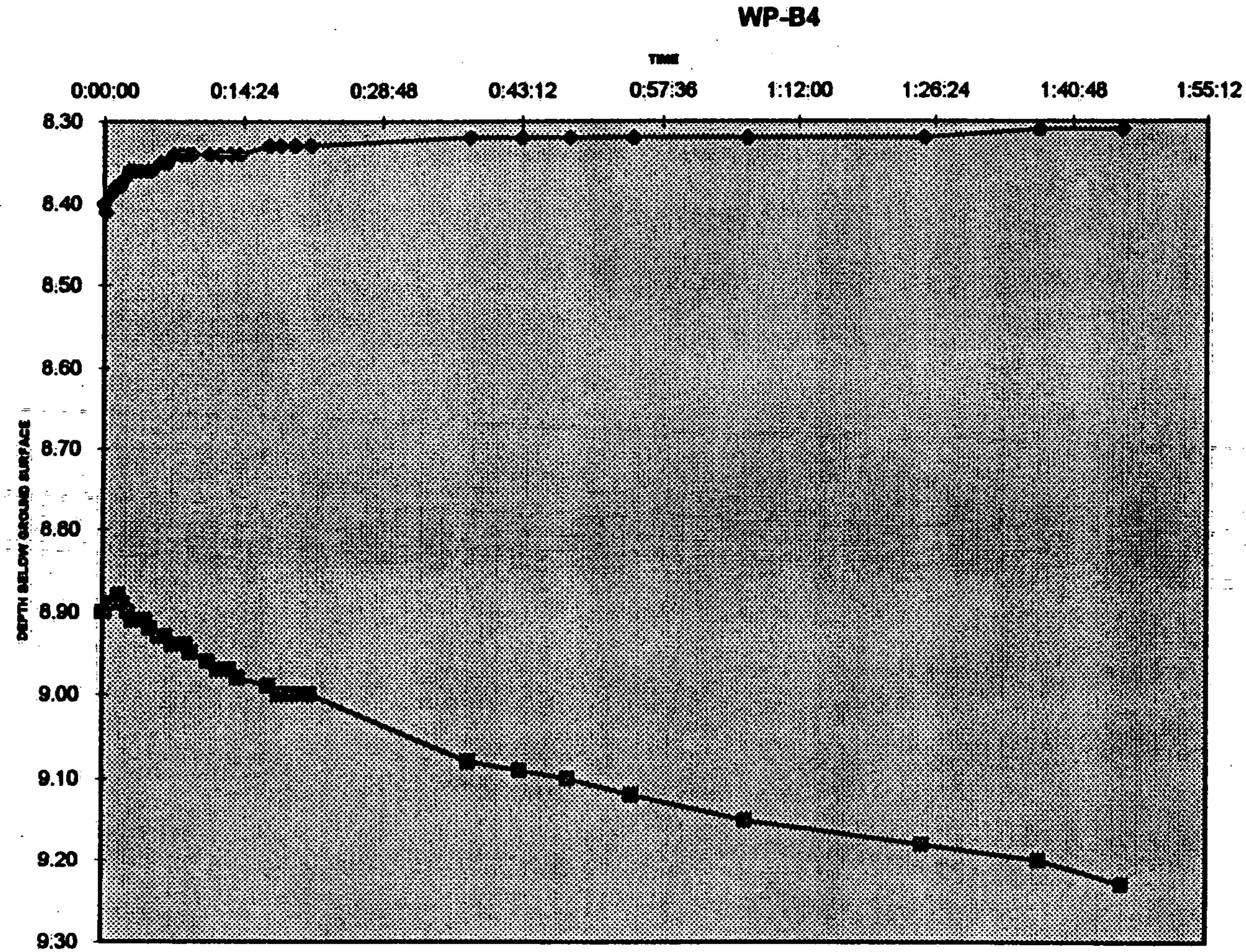
WP-B3 Chart 1



WP-B3
TIME
0:00:00
0:14:24
0:28:48
0:43:12
0:57:36
1:12:00
1:26:24
1:40:48
1:55:12
9.70
9.80
9.90
10.00
10.10
10.20
10.30
10.40
DEPTH BELOW GROUND SURFACE

TABLE 5		
Bail-Down Test Performed At WP-B4		
Specific Gravity = 0.91		
ELLAPSED TIME	DEPTH TO PRODUCT (FEET)	DEPTH TO WATER (FEET)
0:00:00	8.40	8.90
0:00:11	8.41	8.90
0:00:37	8.39	8.89
0:01:05	8.38	8.89
0:01:39	8.38	8.88
0:02:04	8.37	8.89
0:02:34	8.36	8.90
0:03:08	8.36	8.91
0:03:43	8.36	8.91
0:04:23	8.36	8.91
0:04:53	8.36	8.92
0:05:46	8.35	8.93
0:06:26	8.35	8.93
0:07:08	8.34	8.94
0:07:55	8.34	8.94
0:08:35	8.34	8.94
0:09:05	8.34	8.95
0:10:50	8.34	8.96
0:11:55	8.34	8.97
0:13:02	8.34	8.97
0:13:58	8.34	8.98
0:17:05	8.33	8.99
0:18:14	8.33	9.00
0:19:43	8.33	9.00
0:21:21	8.33	9.00
0:37:47	8.32	9.08
0:43:12	8.32	9.09
0:48:08	8.32	9.10
0:54:37	8.32	9.12
1:06:34	8.32	9.15
1:25:20	8.32	9.18
1:37:23	8.31	9.20
1:46:04	8.31	9.23
2:31:33	8.29	9.29
3:31:53	8.30	9.37
4:03:37	8.30	9.41

WP-B4 Chart 1



WP-B4
TIME
0:00:00
0:14:24
0:28:48
0:43:12
0:57:36
1:12:00
1:26:24
1:40:48
1:55:12
8.30
8.40
8.50
8.60
8.70
8.80
8.90
9.00
9.10
9.20
9.30
DEPTH BELOW GROUND SURFACE

TABLE 3		
Bail-Down Test Performed At WP-A8		
Specific Gravity = 0.95		
ELLAPSED TIME	DEPTH TO PRODUCT (FEET)	DEPTH TO WATER (FEET)
0:00:00	13.94	13.95
0:00:30	13.94	13.95
0:00:56	13.94	13.95
0:01:28	13.94	13.96
0:01:58	13.94	13.97
0:02:31	13.94	13.98
0:03:03	13.94	13.98
0:03:38	13.94	13.98
0:04:11	13.94	13.98
0:04:39	13.94	13.99
0:05:10	13.94	13.99
0:05:43	13.94	14.00
0:06:14	13.94	14.01
0:06:47	13.94	14.01
0:07:16	13.94	14.02
0:07:51	13.94	14.02
0:08:30	13.94	14.03
0:09:20	13.94	14.04
0:10:03	13.94	14.04
0:10:35	13.94	14.05
0:11:32	13.94	14.06
0:12:24	13.94	14.06
0:13:23	13.94	14.06
0:14:22	13.94	14.06
0:15:02	13.94	14.07
0:15:53	13.93	14.08
0:16:44	13.93	14.06
0:17:42	13.93	14.08
0:18:45	13.93	14.09
0:19:22	13.93	14.09
0:20:09	13.93	14.10
0:27:29	13.93	14.12
0:37:33	13.93	14.14
0:50:35	13.93	14.19
0:58:38	13.93	14.19

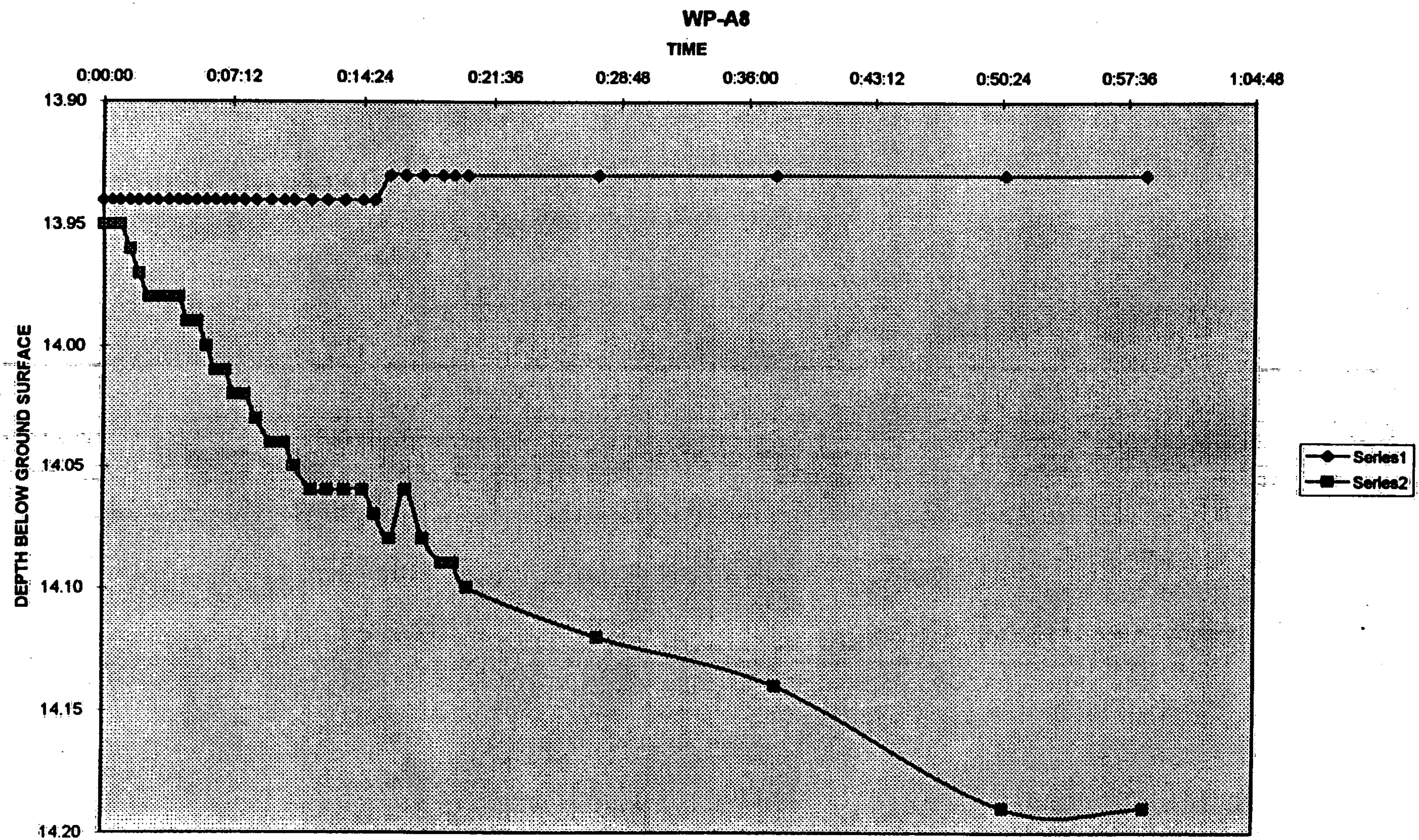

WP-A8
TIME
0:00:00
0:07:12
0:14:24
0:21:36
0:28:48
0:36:00
0:43:12
0:50:24
0:57:36
1:04:48
DEPTH BELOW GROUND SURFACE
13.90
13.95
14.00
14.05
14.10
14.15
14.20
Series1
Series2

TABLE 7		
Bail-Down Test Performed At MW-11(S)		
Specific Gravity = 0.93		
ELLAPSED TIME	DEPTH TO PRODUCT (FEET)	DEPTH TO WATER (FEET)
0:00:00	9.75	10.60
0:00:25	9.80	10.58
0:00:52	9.78	10.57
0:01:25	9.76	10.57
0:01:49	9.75	10.56
0:02:19	9.74	10.55
0:02:49	9.73	10.56
0:03:18	9.73	10.55
0:03:48	9.72	10.55
0:04:15	9.72	10.56
0:04:47	9.71	10.56
0:05:19	9.71	10.56
0:06:17	9.70	10.57
0:07:06	9.70	10.57
0:08:16	9.70	10.59
0:09:22	9.69	10.60
0:10:24	9.69	10.61
0:13:23	9.69	10.64
0:16:27	9.68	10.65
0:22:25	9.68	10.70
0:30:22	9.67	10.75
1:18:37	9.65	10.95
1:30:01	9.66	10.96
2:16:36	9.65	11.03
2:46:58	9.65	11.08

MW-11(S)

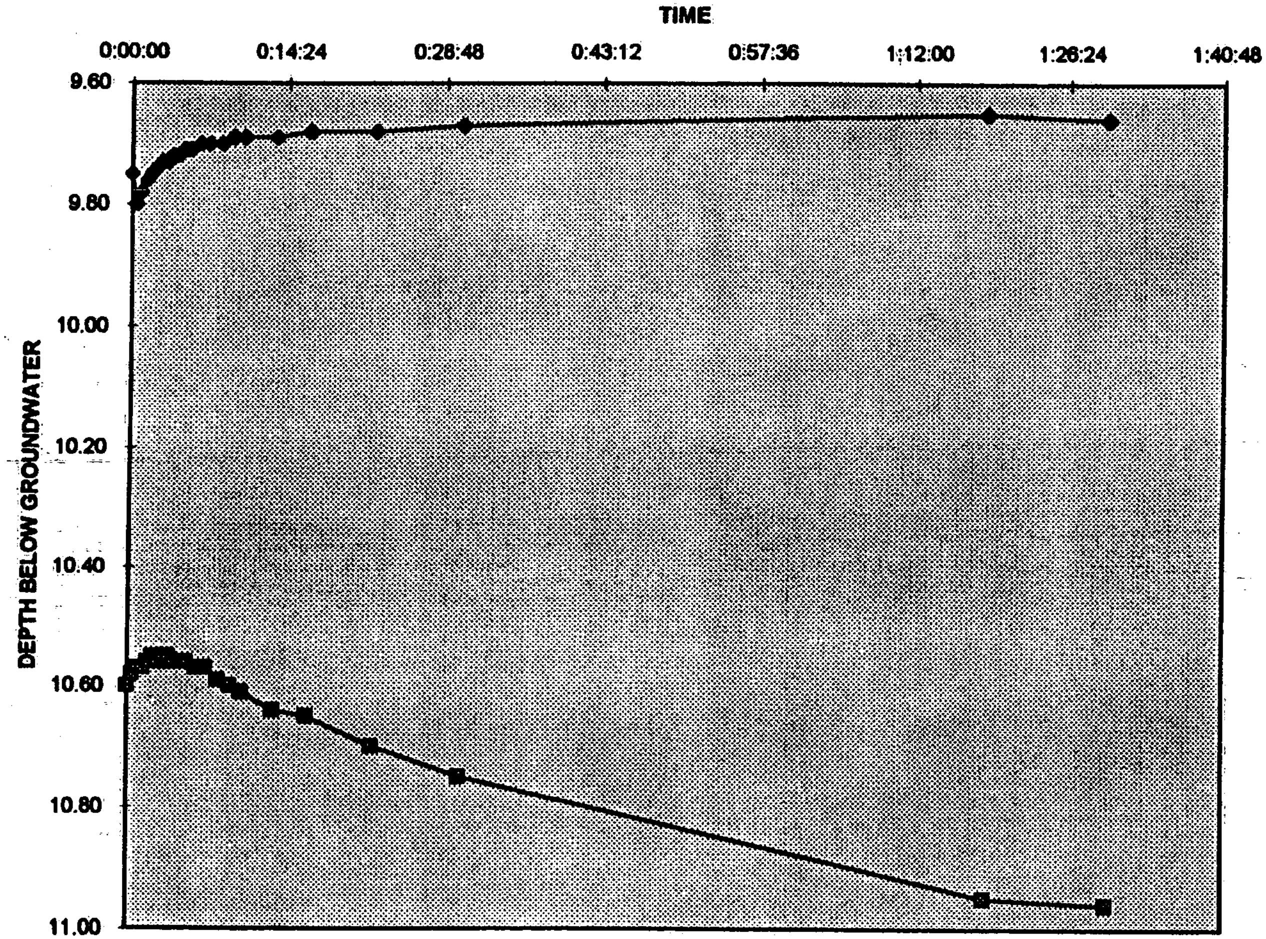

TIME
0:00:00
0:14:24
0:28:48
0:43:12
0:57:36
1:12:00
1:26:24
1:40:48
DEPTH BELOW GROUNDWATER
9.60
9.80
10.00
10.20
10.40
10.60
10.80
11.00

TABLE 2		
Bail-Down Test Performed At WP-A7		
Specific Gravity = 0.97		
ELLAPSED TIME	DEPTH TO PRODUCT (FEET)	DEPTH TO WATER (FEET)
0:00:00	11.57	11.76
0:00:31	11.57	11.76
0:01:04	11.49	11.72
0:01:36	11.48	11.69
0:02:10	11.46	11.67
0:02:38	11.45	11.67
0:03:04	11.43	11.67
0:03:34	11.42	11.66
0:04:06	11.41	11.66
0:04:40	11.40	11.66
0:05:15	11.40	11.67
0:06:19	11.37	11.67
0:07:17	11.36	11.67
0:08:15	11.35	11.68
0:09:25	11.34	11.70
0:10:15	11.35	11.74
0:11:09	11.34	11.74
0:12:24	11.34	11.75
0:13:11	11.33	11.75
0:14:08	11.33	11.76
0:15:02	11.32	11.76
0:16:02	11.32	11.78
0:17:23	11.31	11.79
0:20:41	11.31	11.81
0:22:38	11.30	11.84
0:25:51	11.29	11.88
0:28:32	11.29	11.91
0:31:41	11.29	11.94
0:33:51	11.28	11.96
0:37:57	11.28	12.00
0:40:42	11.28	12.04
0:45:13	11.28	12.09
0:49:57	11.30	12.15
0:54:39	11.27	12.22
1:02:48	11.28	12.32
1:17:07	11.26	12.43
1:38:07	11.26	12.59

WP-A7 Chart 4

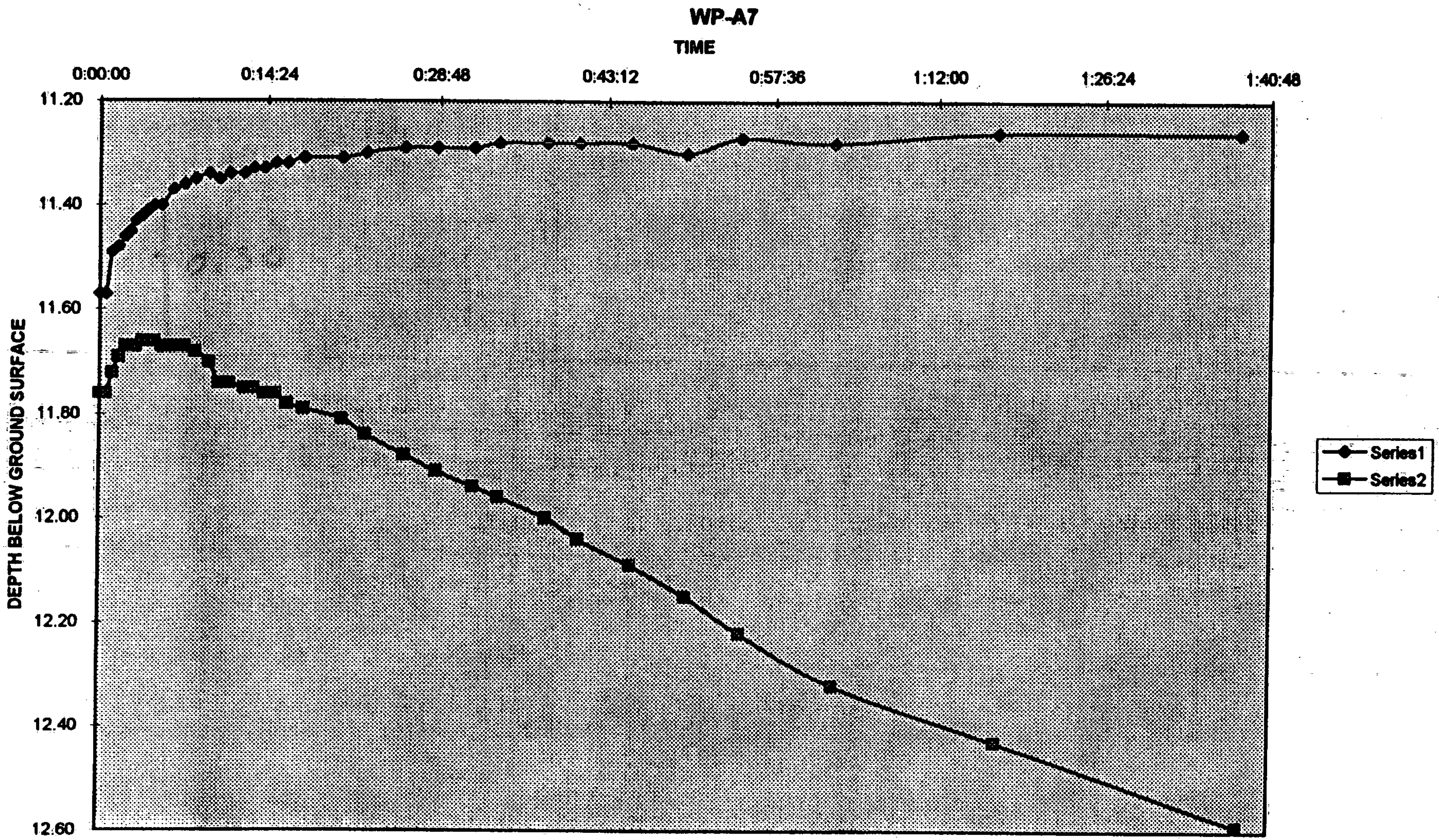

WP-A7
TIME
0:00:00
0:14:24
0:28:48
0:43:12
0:57:36
1:12:00
1:26:24
1:40:48
11.20
11.40
11.60
11.80
12.00
12.20
12.40
12.60
DEPTH BELOW GROUND SURFACE
Series1
Series2

TABLE 8B				
Bail-Down Test Performed At MW-1(R)				
Conducted on 8/16/95				
Specific Gravity = 0.90				
ELLAPSED TIME	DEPTH TO PRODUCT (FEET)	DEPTH TO WATER (FEET)		
0:00:00	11.65	12.56		
0:00:30	11.65	12.57		
0:01:00	11.65	12.57		
0:01:35	11.65	12.56		
0:02:15	11.65	12.56		
0:02:52	11.65	12.55		
0:03:22	11.65	12.56		
0:03:54	11.65	12.55		
0:04:22	11.65	12.55		
0:05:27	11.65	12.56		
0:07:05	11.65	12.56		
0:08:20	11.65	12.56		
0:09:35	11.65	12.57		
0:10:20	11.64	12.57		
0:11:45	11.64	12.58		
0:12:59	11.64	12.57		
0:14:12	11.64	12.58		
0:15:15	11.64	12.58		
0:20:20	11.65	12.59		
0:23:55	11.64	12.60		
0:27:25	11.64	12.60		
0:32:05	11.64	12.62		
0:34:40	11.64	12.62		
0:39:20	11.64	12.63		
0:43:28	11.64	12.64		
0:48:50	11.64	12.66		
0:54:50	11.64	12.66		
0:59:50	11.64	12.67		
1:04:50	11.64	12.67		
1:07:35	11.64	12.68		

MW-1(R) Chart 2

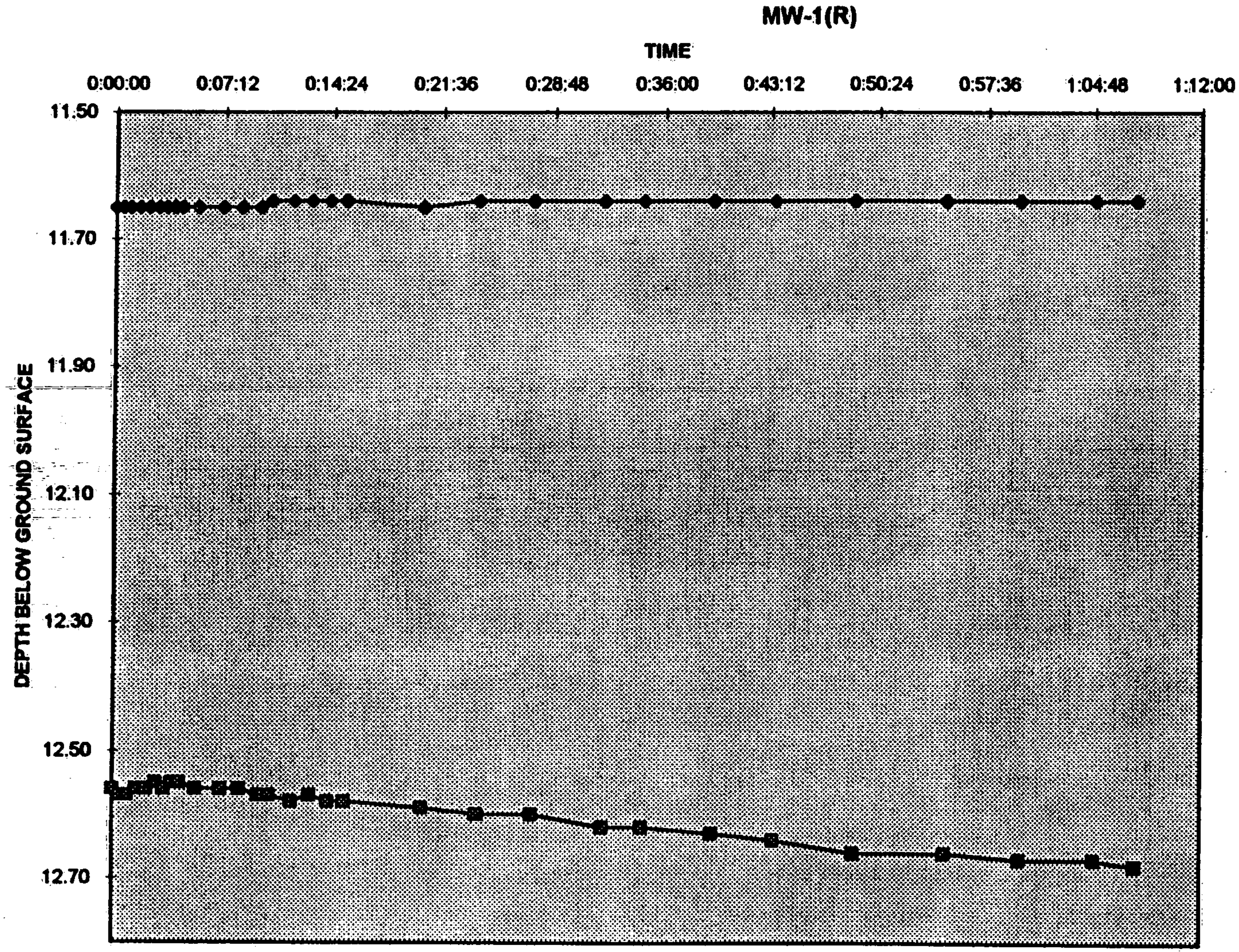

MW-1(R)
TIME
0:00:00
0:07:12
0:14:24
0:21:36
0:28:48
0:36:00
0:43:12
0:50:24
0:57:36
1:04:48
1:12:00
11.50
11.70
11.90
12.10
12.30
12.50
12.70
DEPTH BELOW GROUND SURFACE

TABLE 6		
Bail-Down Test Performed At WP-B5		
Not Enough Product Thickness to Measure Specific Gravity		
ELLAPSED TIME	DEPTH TO PRODUCT (FEET)	DEPTH TO WATER (FEET)
0:00:00	8.77	8.77
0:00:18	8.72	8.72
0:00:43	8.70	8.70
0:01:13	8.69	8.69
0:01:50	8.68	8.68
0:02:40	8.67	8.68
0:03:07	8.67	8.67
0:03:41	8.67	8.67
0:04:11	8.67	8.67
0:04:52	8.66	8.66
0:05:26	8.66	8.66
0:06:12	8.66	8.67
0:07:43	8.66	8.67
0:08:57	8.66	8.68
0:10:56	8.66	8.68
0:14:05	8.66	8.68
0:18:56	8.66	8.68
0:25:16	8.66	8.68
0:40:40	8.66	8.68
0:58:03	8.66	8.70
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2:01:53	8.65	8.70
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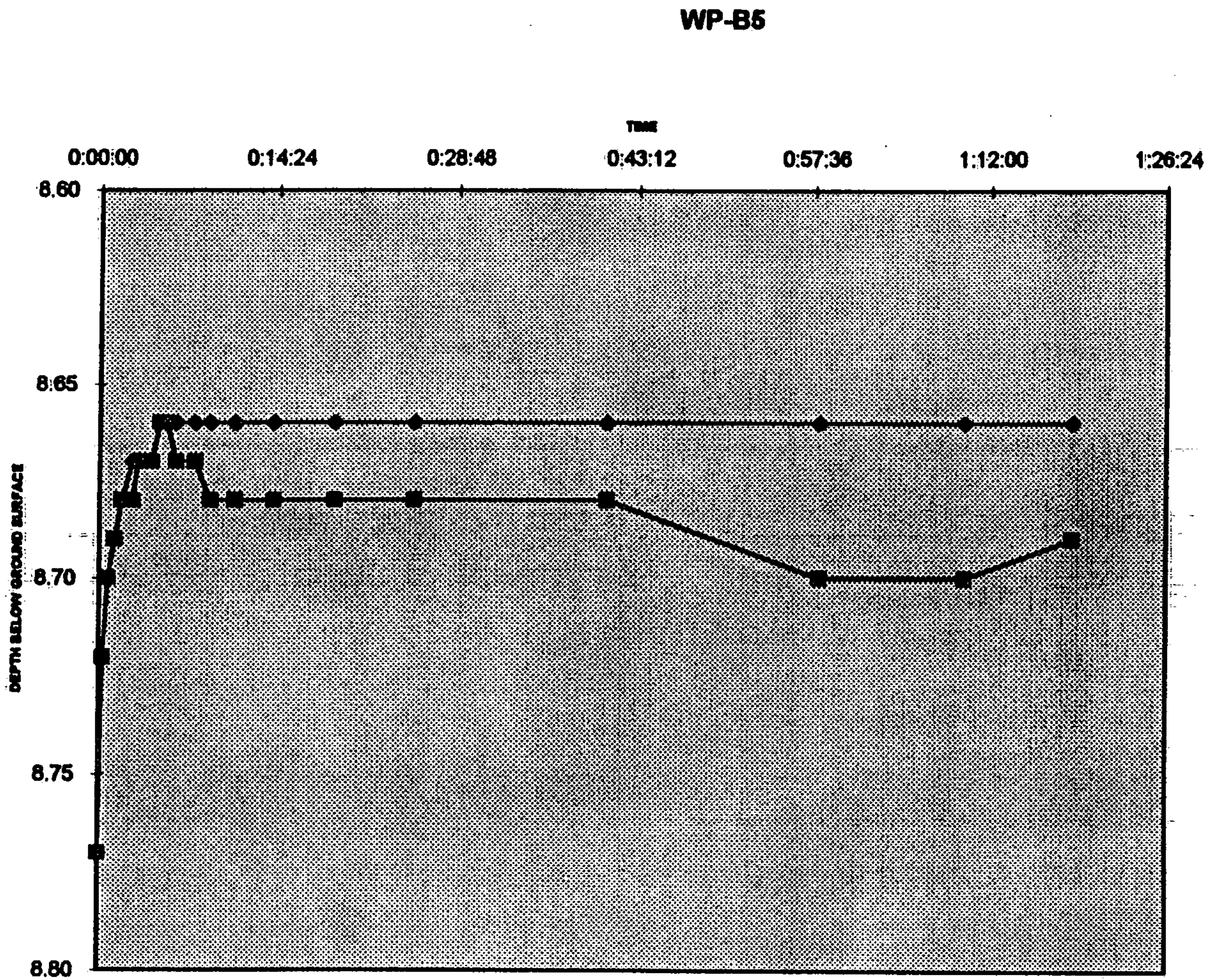
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1:12:00
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8.60
8.65
8.70
8.75
8.80
DEPTH BELOW GROUND SURFACE

DETERMINING REALISTIC TIME FRAMES FOR FREE HYDROCARBON RECOVERY

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ABSTRACT

Free phase hydrocarbon product occurs as perched zones on the capillary fringe beneath numerous petroleum-handling facilities. Under such site conditions, too much emphasis is placed on the time frame required for remediation by federal, state and local regulators, notably in respect to monitoring the efficiency and effectiveness of the respective remediation program. The time required for remediation within the scope of present day technology is a calculated or educated guess at best. Typically, remediation duration is determined by a number of estimates. These estimates have innate compounding errors. Areas of estimation include physical measurement accuracy,"true" versus apparent thickness, validity of bail-down testing, extrapolation of free hydrocarbon product thicknesses between monitoring points, contouring of thickness maps, extrapolation of geologic information, planimetering and estimation of porosity, specific yield and retention, all of which are key factors used in ultimately determining the volume of free hydrocarbon product in place.

Once an initial estimated volume is determined, pilot testing of a recovery system should commence to determine recovery rates.

Factors that will affect recovery rates include the areal distribution and geometry of the free hydrocarbon plume, type and number of recovery system(s) selected, and the performance or efficiency of these systems with time. Effectiveness of the recovery program is thus best estimated based on volume recovered to date divided by the total volume that is considered recoverable.

Remediation time frames at free hydrocarbon recovery sites can be estimated. However, regulators at all levels need to be aware of the large number of compounding errors associated with these calculations. Estimations should be used with extreme caution, because they are usually overestimations. Once a realistic time frame for remediation is mutually agreed upon, it should be clearly understood that it is flexible. It is recommended that a range be initially determined and that as a project progresses and new data is introduced, the remediation time frame be adjusted accordingly.

INTRODUCTION

A large number of petroleum-handling facilities, including petroleum refineries, are included on the U.S. Environmental Protection Agency's National Priorities List (U.S. Environmental Protection Agency, 1986). In the Los Angeles Coastal Plain, for example, a minimum of 17 oil refineries and tank farms have been designated as health hazards. This designation reflects the petroleum residues from such facilities that migrate through the subsurface resulting in the presence of free hydrocarbon plumes on the capillary fringe overlying the water table. Although several of these refineries are listed as hazardous waste sites and remediation is being promulgated under RCRA, a majority of such facilities are undergoing remediation under the California Regional Water Quality Control Board Order 85-17 adopted in February, 1985. This order requires, in part, delineation of free hydrocarbon plumes and other groundwater pollutants which may affect subsurface soils and/or groundwater under such facilities, subsequent recovery of free hydrocarbon, aquifer restoration (dissolved phases) and soil remediation (residual hydrocarbon).

Subsurface site remediation begins with delineation and estimations of the volume of free hydrocarbon present. Some of these free hydrocarbon plumes encompass tens to hundreds of acres in lateral extent and up to several hundred and thousands recoverable barrels (42 gallons/barrel) in total volume. However, it is generally estimated that up to only 50 percent (although typically 20 to 30 percent) of the total pore volume of free hydrocarbon present is recoverable by conventional means.

As part of the regulatory process, the reviewing agency requests not only information regarding lateral extent, but also evaluation of total volume present, percent recovered to date if recovery has been in progress for some time and the overall time frame for complete recovery of all free hydrocarbon. This information is then used to monitor the efficiency and effectiveness of the recovery and overall remediation program. To accurately respond to these requests is difficult. This difficulty reflects problems associated with determination of product type, true versus apparent thickness and notably, free hydrocarbon product volume in both passive and active systems. Presented in this paper is a discussion of the difficulties and limitations encountered in estimating volume and recoverability of free hydrocarbon product. Also presented are two case histories illustrating the problems associated with volume determinations and their use in monitoring the effectiveness of the free hydrocarbon recovery programs. Not discussed is the migration of petroleum hydrocarbon in the subsurface which is presented by Schwille (1967), API (1980), Farmer (1983) and Dragun (1988).

VOLUME DETERMINATION DIFFICULTIES

Field Measurement Techniques

Free hydrocarbon product in the subsurface is typically delineated and measured by the utilization of groundwater monitoring wells. The thickness of free hydrocarbon product in a well is typically determined using either a steel tape with water-and-oil-finding paste or commercially available electronic resistivity probes. Either method can provide data with an accuracy to 0.01 of a foot. However, if the free hydrocarbon product is emulsified or highly viscous, significant error can result. In addition, measurement using electronic resistivity probes can be misleading if the battery source is weak.

Apparent Versus True Thickness

While monitoring wells have provided some insight as to the extent and general geometry of the plume, as well as the direction of ground water flow, difficulties persist in determining the "true" thickness (Hampton, 1988) and, therefore, the volume and ultimately the duration of recovery and remediation. One difficult aspect of monitoring subsurface hydrocarbons is that accumulations in monitoring wells do not directly correspond to the actual or true thickness in the formation (Blake and Fryberger, 1983; Blake and Hall, 1984; Hall, et al., 1984).

The thickness of free hydrocarbon product as measured in a monitoring well is an apparent thickness rather than a "true" or formation thickness (Blake and Hall, 1984; Hall, et al., 1984). The difference between "true" and apparent thickness has been attributed to the capillary fringe. The capillary fringe height is dependent upon the grain size distribution as summarized in Table 1 (Bear, 1979). Coarse grained formations contain large pore spaces that greatly reduce the height of the capillary rise. Fine grained formations have much smaller pore spaces which allow a higher capillary height.

TABLE 1

GENERAL CAPILLARY RISE FOR CERTAIN SOIL TYPES

Soil Type	Capillary Rise (inches)
Coarse Sand	3/4 - 2
Sand	4 - 14
Fine Sand	14 - 27
Silt	27 - 59
Clay	78 - 100+

Since hydrocarbon and water are immiscible fluids, the hydrocarbons are perched on the capillary fringe above the actual water table. The typical physical relationships that exist is illustrated in Figure 1.

Since the free hydrocarbon product occurs within and above the water capillary fringe, once the monitoring well penetrates and destroys this capillary fringe, free hydrocarbon product migrates into the well bore. The free water surface that stabilizes in the well will be lower than the top of the surrounding capillary fringe in the formation, thus, hydrocarbons will flow into the well from this elevated position. Product will continue to flow into the well and depress the water surface until a density equilibrium is established. To maintain equilibrium, the weight of the column of hydrocarbon will depress the water level in the well bore. Therefore, a greater apparent thickness is measured than actually exists in the formation.

The measured or "apparent" hydrocarbon thickness is not only dependent upon the capillary fringe but also by the actual hydrocarbon thickness in the formation. Thus, the measured or "apparent" hydrocarbon thickness is greater for fine grained formations and less for coarser grained formations which may be more representative of the true thickness. In areas of relatively thin hydrocarbon accumulations, the error between the apparent well thickness and actual formation thickness can be more pronounced than in areas of thicker accumulations. The larger error reflects the relative difference between the thin layer of hydrocarbon in the formation and the height it is perched above the water table. The perched height is constant for thick and thin accumulations; however, a thick accumulation can depress and even destroy the capillary fringe. The relative difference between apparent and "true" hydrocarbon thickness increases with decreasing formation grain size and increasing specific gravity of hydrocarbon (Hall et al., 1984).

The thickness measured in a monitoring well with free hydrocarbon product situated on a perched layer at some elevation above the water table, can produce even larger associated thickness error. This commonly occurs when the well penetrates the perched layer and is screened from the perching layer to the water table. The hydrocarbon then flows into the well from the higher or perched elevation. The accumulated apparent thickness is a direct result of the difference of their respective heights. If a situation such as this exists, a greater error or difference and weight of the column of hydrocarbon should be accounted for in determining true thickness.

Additionally, fluctuations in the water table due to recovery operations or seasonal variations have a direct effect upon the apparent or measured hydrocarbon thickness (Yaniga, 1984). As the water table elevation declines gradually due to seasonal variations for instance, an exaggerated apparent thickness occurs reflecting the additional hydrocarbon that accumulated in the monitoring well. The same is true for an area undergoing recovery operations where the groundwater elevation is lowered through pumping, thicker apparent thicknesses may be observed.

The reverse of this effect has been documented at recovery sites. When sufficient recharge to the groundwater system through seasonal precipitation events or cessation of recovery well pumping occurs with the water table at a slightly higher elevation, thinner hydrocarbon thicknesses may be observed (Yaniga, 1984). During this situation a compression of the capillary zone occurs, lessening the elevation difference between the free water table and the hydrocarbon which reduces the apparent thickness.

Empirical Approach To Estimate Volume

Prior to initiation of a free hydrocarbon recovery strategy, the total hydrocarbon and recoverable hydrocarbon volume is estimated. This estimate is dependent on the determination of true hydrocarbon thickness which can be derived empirically or in conjunction with bail-down testing field methods. Initially, the measurement of apparent free hydrocarbon product thicknesses in monitoring wells is conducted. The data generated is then used to develop an apparent hydrocarbon thickness contour (isopach) map. Once developed, planimetering is performed to derive the areal coverage of incremental apparent hydrocarbon thicknesses. The greater the coverage and number of data points (monitoring wells), the smaller the chosen increment for planimetering. Although apparent thicknesses can vary between monitoring points depending on the thickness of the capillary fringe, calculated thickness values between monitoring points are approximated. Thus, the capillary fringe, hence the apparent thickness, is assumed to be constant between monitoring points. Upon completion of planimetering, the volume of soil encompassed by the free hydrocarbon product plume (Vs) is estimated. This value is then multiplied by an "assumed" porosity ($\emptyset$) value, based on soil types encountered during the subsurface characterization process to calculate the total apparent volume (Va) present as shown below:

$V_a = V_s \times \emptyset$, where

V_a = Total Apparent Volume of Hydrocarbon Present

V_s = Volume of Soil Encompassed by Free Hydrocarbon Product

$\emptyset$ = Porosity (assumed)

Since the water table as measured in the well is depressed by the weight of the hydrocarbon, a corrected depth to water is calculated:

PTap = DTW - DTP

CDTW = Static DTW - (PTap x G), where

CDTW = Corrected Depth to Water

DTW = Depth to Water, measured

DTP = Depth to Product, measured

PTap = Apparent Product Thickness

G = Specific Gravity of Product at 60° F.

A correction factor is then applied for capillary fringe effects. This factor is empirically derived reflecting the corrected depth to water as shown below:

Capillary Fringe (CF) = (CDTW - DTP) - PTac, where

CF = Capillary Fringe Thickness

CDTW = Corrected Depth to Water, calculated

DTP = Depth to Product, measured

PTac = Actual Product Thickness

Calculation of total apparent volume does not, however, take into consideration the specific yield of the formation. Specific yield is the percentage of the mobile free hydrocarbon product which will drain and be recovered under the influences of gravity. This value is dependent on flow characteristics of the hydrocarbon as well as the geologic formation characteristics. Typical values may range from 5 to 20 percent. The total apparent volume is multiplied by an "assumed" specific yield for the particular area to obtain the volume of recoverable hydrocarbons:

$H_r = S_y \times V_a$, where

H_r = Recoverable Hydrocarbon

S_y = Specific Yield

V_a = Total Apparent Volume of Hydrocarbon Present

Field Approach To Estimate Volume

In lieu of using an empirical approach as discussed above, total apparent volume can be calculated using "true" thickness values derived from bail-down testing. Bail-down testing is a widely used field method to evaluate the "true" thickness of free hydrocarbon product in a monitoring well. Bail-down testing was originally used as a field check method to determine potential locations for free hydrocarbon recovery wells. All monitoring wells at a site that had a measurable thickness of free hydrocarbon product were typically tested. Whether or not all the free hydrocarbon product could be removed from the well and the volume of hydrocarbon bailed were general indicators of areas for "potentially good" recovery.

Bail-down testing field procedures are similar to those performed for in-situ permeability tests and involves the measuring of the initial "apparent" thickness in the monitoring well by an oil-water interface gauging probe. Only free standing hydrocarbon is then bailed from the well until all of the hydrocarbon is removed or no further reduction in thickness can be achieved. Measured over time are levels of both depth to product (DTP) and depth to water (DTW). Typically, the time increments for measurement follow the same sequence as monitored during an aquifer pumping test. The test is considered complete when the well levels have stabilized for three consecutive readings or if a significant amount of time has elapsed and the levels have reached 90 percent of the original measurements.

If the apparent thickness is greater than actual thickness, and the thickness in the well has been reduced to less than true during bailing, then at some point during fluid recovery the apparent thickness equals the true thickness (Gruszczenski; 1987). During recovery of fluid levels in the well, the top of product in the well rises to its original level. However, the top of water (product/water interface) initially rises and then falls. The fall is due to displacement of water in the well reflecting an over accumulation of product on the water surface. The point at which the depth-to-water graph changes from a positive to negative slope is referred to as the "inflection point". At the "inflection point", the measured thickness is interpreted to equal the true thickness.

Bail-down tests involve the estimation of true thickness via the graphical presentation of depth-to-product, depth-to-water and thickness versus time as measured during the fluid recovery period in each well (Figure 2).

An "inflection point time", corresponding to the "inflection point" on the depth-to-water graph, is determined from which the true thickness can be estimated on a graph showing thickness versus time. Typically, two basic curves are produced (Gruszczenski, 1987): type one curves reflect wells with product accumulation less than several inches while type two curves reflect product accumulation greater than 12 inches. The latter indicates an inflection point prior to stabilization of product and water levels, and has been reported by Gruszczenski (1987) to indicate a 70 to 95 percent reduction between the apparent and actual thickness.

When bail-down test results do not conform to the theoretical response anticipated, maximum theoretical values can be determined by subtracting the static depth-to-product from the corrected depth-to-water. Thicknesses provided in this manner are conservative in that true thicknesses must be less than or equal to these values, and thus, overestimates the actual thickness by an amount equal to the thickness of the capillary zone.

Although bail-down testing is a relatively simple field procedure, the analysis and evaluation of the data is speculative. The method contains a number of steps where errors can easily be introduced. Bail-down testing results are relied upon to determine "true" thickness in a monitoring well and is an initial step and basis for calculating a volume and subsequently a recoverable volume. Some of the areas where error(s) can easily be introduced include:

- Accuracy of the measuring device used for the initial gauging and recovery of the levels after bailing;
- Operator error in measuring and recording levels with time;
- Inability of operator to collect early recovery data due to rapid rising well levels;
- Bailing groundwater in addition to product from a low yielding formation;
- Lack of a theoretical response or inflection point due to an inordinate length of time for water recovery;
- Variable accumulation rates of product caused by borehole effects: and
- Evaluation of type curves and selection of an inflection point.

If bail-down testing has innate compounding errors within itself, these errors can only be further compounded since the remaining calculations, extrapolations and evaluations are based upon this initial step. Although discussion of the validity of bail-down testing to determine "true" thickness is beyond the scope of this paper, this procedure remains essentially unproven. However, this method can be used as a useful supportive tool in comparing the true thickness data generated from bail-down testing to those derived empirically, thus, resulting a range for total free hydrocarbon product volume present and subsequent recoverable amounts.

RECOVERABILITY OF FREE HYDROCARBON PRODUCT

Relative Permeability

The potential for recovery of free hydrocarbon product is governed by the viscosity, density and true saturated thickness of the hydrocarbon in the formation, the residual water saturation and the permeability of the formation. These factors determine the relative permeability of the formation to the hydrocarbon. The relative permeability is a measure of the relative ability of hydrocarbon and water to migrate through the formation as compared to a single fluid. It is expressed as a fraction or percentage of the permeability in a single fluid system. Relative permeability must be determined experimentally for each formation material and each combination of fluid saturations and fluid properties. During hydrocarbon recovery, their ratios are constantly changing. Graphs of relative permeability are generally similar in pattern to that shown in Figure 3.

Some residual water remains in the pore spaces, but as discussed by Levorsen (1967) and illustrated in Figure 3 (also presented by Levorsen), water does not begin to flow through the example material until its water saturation reaches 20 percent or above. Water at the low saturation is interstitial or "pore" water, held by capillary forces, preferentially wets the material and fills the finer pores. As water saturation increases from 5 to 20 percent, hydrocarbon saturation decreases from 95 to 80 percent where, to this point, the formation permits only hydrocarbon to flow, not water. Where the curves cross (at a saturation of 56 percent for water and 44 percent for hydrocarbon) the relative permeability is the same for both fluids. Both fluids flow, but at a level of less than 30 percent of what each fluid's flow would be at 100 percent saturation. As the water saturation rises, the water flows more freely and hydrocarbon flow decreases. When the hydrocarbon saturation approaches 10 percent, the hydrocarbon becomes immobile, allowing only water to flow. For the example given, the hydrocarbon residual saturation is 10 percent pore saturation limited by the fluid density and viscosity and the formation permeability.

The relations shown in Figure 3 have a wide application to problems of fluid flow through permeable material. One of the most important applications for recovery of hydrocarbon is that there must be at least 5 to 10 percent saturation with the nonwetting fluid and 20 to 40 percent saturation with the wetting fluid before flow occurs. Thus for hydrocarbon (the nonwetting fluid), there must be a minimum of 5 to 10 percent saturation of the pore space before the fluid can move through the partially-saturated or unsaturated formation and accumulate. Conversely, every hydrocarbon accumulation has a quantity of hydrocarbon which is not mobile since it is at or below a saturation of 5 to 10 percent also exists, and is thus not recoverable.

Residual Hydrocarbon

The recoverability of hydrocarbon from the subsurface refers to the amount of mobile hydrocarbon available. Hydrocarbon that is retained in the unsaturated zone is not typically recoverable by conventional means. Additional amounts of hydrocarbon that are unrecoverable by conventional methods include the immobile hydrocarbons associated with the water table capillary zone. Residual hydrocarbon is pellicular or insular, and is retained in the aquifer matrix. In general, as viscosity of the hydrocarbon increases and grain size decreases, the residual saturation increases. Typical residual saturation values for unsaturated, porous soil are presented by Concawe (1979) and tabulated in Table 2.

TABLE 2

TYPICAL RESIDUAL SATURATION VALUES FOR UNSATURATED SOIL

Soil Type	Oil Retention Capacity (liters/m^3)
Stone, coarse gravel	5
Gravel, coarse sand	8
Coarse sand, medium sand	15
Medium sand, medium sand	25
Fine sand, silt	40

These values are then multiplied by a correction factor to account for hydrocarbon viscosity. Correction factors for different hydrocarbon types are:

- 0.5 for low viscosity products (gasoline);
- 1.0 for keroseneandgas oil; and
- 2.0 for more viscous oils.

The American Petroleum Institute (1980) has presented some similar guidelines for estimating residual saturation. Basing their work on a "typical" soil with a porosity of 30 percent, the API gives residual saturation values noted as a percentage of the total porosity of the soil as follows:

- 0.18 for light oil and gasoline;
- 0.15 for diesel and light fuel oil; and
- 0.20 for lube and heavy fuel oils.

Similar studies done by Hall, et al. (1984) on hydrocarbon of lower API gravities (i.e., gravities between 34 and 40 degrees) show that specific retention for more viscous hydrocarbons can range between 35 to 50 percent of the pore volume for fine sands with porosities of approximately 30 percent. The loss due to retention in the aquifer as the hydrocarbon migrates to the recovery well can be significant. Wilson and Conrad (1984) claim that residual losses are much higher in the saturated zone (i.e., capillaryzone) then in the unsaturated zone.

Comparisons of the estimated volume to the actual volume recovered proves to be the only reasonable procedure for assessing the recoverable volume considering all the variables involved. These comparisons indicate that the volume of hydrocarbon retained in the aquifer is higher than published residual saturation values. Based on experience for gasoline and low viscosity hydrocarbons, the recoverable volumes have ranged from 20 to 60 percent of the pore volume in fine to medium sands.

Other Factors

In addition to factors concerning relative permeability and residual hydrocarbon, areal distribution of the plume and site specific physical constraints can have a significant impact upon the degree of recoverability. A relatively small plume in areal extent with concentrated thicknesses is more recoverable, for example, than a thin plume with a large areal distribution. Site specific physical constraints may have a major impact upon the recoverability of the plume. The problem centers around the difficulty in locating recovery well(s) in their optimum location without conflicting with the facility layout. Furthermore, most recovery programs generate contaminated groundwater. Depending on the size of the facility and the scale of the recovery project, the recoverability of hydrocarbon and respective time frame may be limited and highly dependent on the amount of water the facility can handle, and the subsequent treatment and disposal options available (Paczkowski et al., 1988).

CASE STUDIES

Case Study A

The site for Case Study A is a 100-acre abandoned hydrocarbon bulk storage tank farm. This case study is an excellent example of the relationship between the effects of recovery and volume determinations since the site will not have a continual recharge of hydrocarbon to the existing plume. This case study is also discussed since it presents a scenario whereby the fullest effects of recovery on the total estimated volume and recoverable volume could be readily evaluated.

The site is situated on the Los Angeles coastal plain and underlain by an alluvial sequence of unconsolidated, stratified, laterally discontinuous deposits of sand, silty sand, clayey silt and silty clay of Recent and Upper Pleistocene age. A thin veneer of recent deposits immediately underlies the site. These deposits are difficult to distinguish from the underlying Upper Pleistocene deposits due to similarities in lithology.

Hydrocarbons, specifically gas-oil, were initially stored at the site as early as 1962. The site remained in operation for a period of fifteen years and then taken out of operation in 1977 when the facility owner discovered losses from storage structures at the site. Initially, six one-pump recovery wells and three monitoring wells were installed by the owner. The systems operated throughout most of 1977 and approximately 38,000 barrels of gas-oil were recovered.

Recovery at the site ceased near the end of 1977, and resumed sometime in 1979, and operated intermittently for the period of one year although little gas-oil was recovered during this period.

In late 1982, a consultant was retained to delineate the extent of the hydrocarbon plume and design and implement a recovery system. Initially, five additional monitoring wells were completed to characterize subsurface conditions. These additional monitoring wells, in conjunction with the existing wells installed by the owner, were plotted, drafted and planimetered. Although the lateral extent of the hydrocarbon plume were not determined, total, available and recoverable volumes were calculated. These calculations were based upon:

- Measured apparent free hydrocarbon product thickness in the well; and
- Laboratory-derived porosity values from actual soil samples.

Volumetric calculations of total and available hydrocarbon for recovery was determined by the empirical method as previously discussed.

A total volume of 476,000 barrels (bbls) was estimated to exist beneath the site; the recoverable volume was estimated to be 200,000 bbls. These estimates were based on data collected from only thirteen monitoring wells.

Two two-pump recovery wells were installed and put into operation in 1983. Additional monitoring wells were installed from 1983 to 1985 to provide further definition of the plume's dimensions. During the late part of 1983, three additional two-pump recovery wells were installed. An additional 76 monitoring wells were subsequently installed to refine the initial volume estimates. By the end of 1985, five recovery wells were in operation and 89 monitoring wells were completed. As of January 1988, 182,000 barrels of gas-oil was produced from the five recovery wells.

Additional volume calculations were made utilizing the additional monitoring well data and production totals of existing recovery wells. The initial volumetric determination did not utilize the empirical method but rather straight forward volume determinations based solely on apparent thickness, porosity and expected recovery rates. The second volume calculations accounted for differences in apparent versus actual thicknesses (Blake and Hall, 1984) and exaggerated thicknesses (Hall, et al., 1984). The original recoverable estimate based upon 13 monitoring wells was 200,000 barrels. A revised total volume estimate of 310,000 barrels was calculated based on the additional data generated. Of the total volume, as in the original estimate, 40 percent recoverability was assumed, and thus, 128,000 bbls were determined to be the revised recoverable volume. With a present estimate of 128,000 bbls recoverable and 182,000 bbls recovered to date, the original estimate would have been 310,000 bbls recoverable. Thus, the recovery system has removed about 58 percent of the recoverable hydrocarbon. A summary of the volumetric calculations is presented in Table 3.

TABLE 3

SUMMARY OF VOLUMETRIC CALCULATIONS

CASE STUDY A

	Number of Monitoring Wells	Estimated Total (bbls)	Estimated Recoverable Volume (bbls)	Estimated Percent Recovered
Estimate 1	13	476,000	200,000	*
Estimate 2	89	310,000	128,000	58

* Free hydrocarbon recovery not yet initiated.

Additional monitoring wells constructed have increased the coverage of the area and accounts for greater detail in delineating the hydrocarbon plume. Thus, new areas of hydrocarbon accumulations were discovered, resulting in increased volume, reflecting greater detail in coverage rather than from actual changes in hydrocarbon volume.

Case Study B

The site for Case Study B is a relatively large, active refinery with a 125,000 barrel per day crude capacity. The site has an extensive tank farm area consisting of tens of acres and a moderate size processing area. The refinery has been in existence for over 70 years. Continual recharge of hydrocarbon to the existing plume volume is likely due to the activity and age of the facility. The site is situated on the western edge of the Atlantic coastal plain in the Mid-Atlantic region of the United States, and is immediately underlain by alluvial deposits comprised of interlayered silty sand and clayey gravel.

A variety of free hydrocarbon products are produced and stored at the facility. The major constituent of the hydrocarbon plume which underlies the site is fuel oil. The facility's owner had installed a series of monitoring and recovery wells; however, inaccurate production records has made the inclusion of this data into this case study impossible. As of early 1987, 69 existing monitoring wells were measured and volumes calculated by the facility. The volumes are derived in a straightforward method accounting only for the apparent thicknesses measured in monitoring wells. The facility estimated that 141,000 bbls existed. Assuming about 50 percent recoverability, 71,000 bbls of the fuel oil was estimated as being recoverable.

In the latter part of 1987, seven additional monitoring wells were installed, aquifer tests conducted, and soil samples analyzed for porosity determination within the hydrocarbon horizon. The empirical method to determine total volumes and recoverable volumes was then applied. Based upon data from 76 monitoring wells, which indicated a formation porosity of 20 percent and a specific yield of 0.22, new total and recoverable volume estimates were prepared. About 190,000 bbls of free hydrocarbon product were estimated to be present. Assuming 35 percent recoverability, the recoverable volume was estimated at 66,500 bbls.

A two-pump recovery well was put into operation during August of 1987. The recovery well was located in an area of the plume of maximum accumulated thickness. Approximately 2500 bbls of fuel oil were produced in four months. In early 1988, all monitoring wells that had an accumulation of hydrocarbon were bail tested. The raw field data from bail testing was graphed and "true" thickness values were determined for each monitoring well. The values were plotted, an inflection point selected, and a "true" thickness evaluated for each monitoring well. The total volume and recoverable volume based upon the "true" thickness were 67,000 and 20,000 bbls, respectively. A table summarizing total and recoverable volume estimates is presented in Table 4.

Total and recoverable volume estimates were also made from the apparent monitoring well thickness data collected during bail testing. This provided the values of empirical verses field for direct comparison. The values were 101,000 bbls and 34,500 bbls for total and recoverable volumes respectively (Table 4).

TABLE 4

ESTIMATED TOTAL AND RECOVERABLE VOLUMES

Method (Date)	Number of Monitoring Wells	Estimated Total Volume (bbls)	Estimated Recoverable Volume (bbls)
Apparent Thickness (Early 1987)	69	141,000	71,000
Empirical (Late 1987)	76	190,000	66,500
Field/bail-testing (Early 1988)	88	67,000	20,000
Empirical (Early 1988)	88	101,000	34,500

Calculations and comparisons were then made between total volume, recoverable volume, and actual production from the area of influence of the recovery well and amount of actual recovered fuel oil. An area of influence contour map for the recovery well was used as an overlay. The overlay was placed on top of three hydrocarbon thickness maps. Total and recoverable volumes within the area of influence of the recovery well were then calculated. Results of these calculations are presented in Table 5. The estimated recoverable volumes range from 3,270 to 11,600 bbls.

TABLE 5

ESTIMATED VOLUME OF TOTAL AND RECOVERABLE FREE HYDROCARBON WITHIN THE AREA OF INFLUENCE

Method (Date)	Estimated Total Volume (bbls)	Estimated Recoverable Volume (bbls)
Empirical Apparent Thickness (5/87)	19,500	5,800
Field True Thickness (2/88)	11,000	3,270
Empirical Apparent Thickness (2/88)	38,700	11,600

These estimates were then compared to actual recovery well production volumes. The recovery well produced 4050 bbls from startup to the time at which bail testing was conducted. From the time bail testing was conducted to the end of June, 1988 the recovery well produced 4100 bbls. Estimated recoverable volume based on the field or bail test method (Table 2) was 3270. Therefore, over 830 bbls were produced, in excess of the bail test estimate. The recovery well is still in production and is currently continuing at the same rate of production.

It does seem unlikely that an increase in volume of hydrocarbon within the area of free hydrocarbon within the area of influence of the recovery well could be on the order of 830 bbls. Although some loss through pipelines and tank bottoms probably occurred, a major loss would have to occur to provide a volume of this magnitude. Additions to the volume via losses is probable; however, determining the actual contribution from various sources is not feasible.

SUMMARY AND CONCLUSION

Time frames for recovery of free hydrocarbon products is limited by numerous factors or estimates, and is often based on an educated guess. These factors or estimates have innate compounding errors in relation to the following:

- Accuracy of physical measurement where high viscosity and emulsified hydrocarbon is encountered;
- Determination of true versus apparent thickness;
- Validity of bail-down test for estimation of true thickness;
- Extrapolation of geologic and hydrogeologic information between monitoring points;
- Extrapolation of hydrocarbon apparent thicknesses between monitoring points;
- Averaging of apparent thicknesses for planimetering; and
- Estimation or assumption for key factors including porosity, specific yield and retention values.

Once an initial estimated volume is determined, pilot testing of a recovery system is initiated to evaluate recovery rates. However, factors which significantly affect recovery rates include the areal distribution and geometry of the free hydrocarbon product plume, type(s) and design of recovery system selected, and the performance and efficiency of the system with time.

Volume determinations and subsequent time frame for recovery of free hydrocarbon product can be estimated. However, regulators at all levels need to be aware of the large number of compounding errors associated with these calculations. Thus, a reasonable time frame for remediation is clearly an estimate.

The progress of recovery efforts cannot be based confidently on free hydrocarbon product thickness maps. Although these maps provide quantification of overall trends, the numerous factors which impact hydrocarbon thicknesses make accurate quantification difficult. Estimate of effectiveness thus is based on volume recovered to date divided by the total volume that is considered recoverable. Furthermore, as the recovery project progresses and new data is introduced, the volume and time frame for recovery should be continually reevaluated and revised.

In determining total and recoverable volumes of hydrocarbon, the factor of recharge to the volume is undeterminable, but realistic. From experience and the case studies provided, developing a range of total and recoverable volumes is suggested. A valid way to determine this range is a comparison of values generated from the empirical and field (bail test) methods. Also as additional monitoring well points are incorporated into the project, this new data needs to be coupled with existing data and revised estimates made. Finally, comparisons of the estimated recoverable volumes to the actual volume produced proves to be the only reasonable procedure for estimating the recoverable volume considering all the variables involved.

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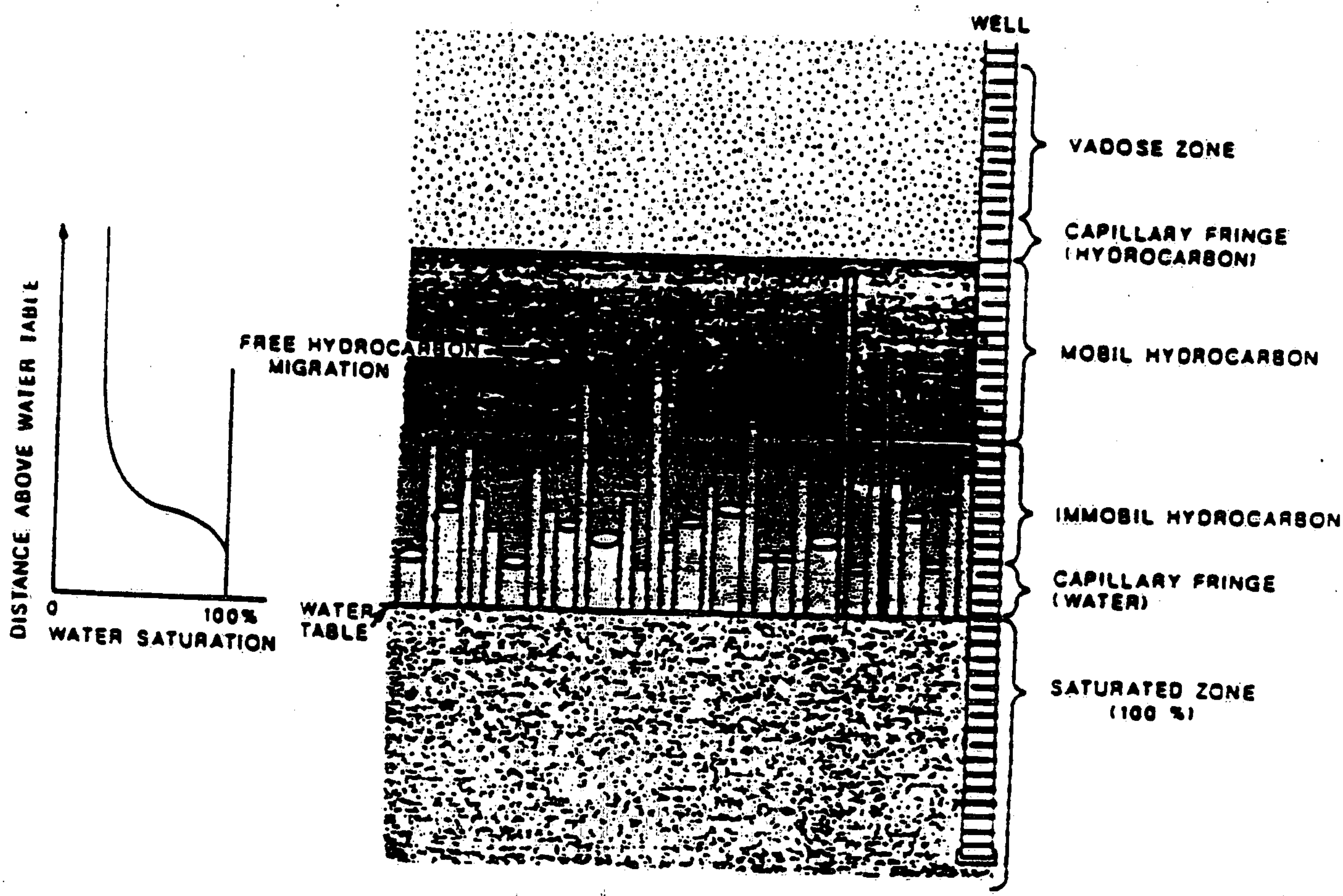
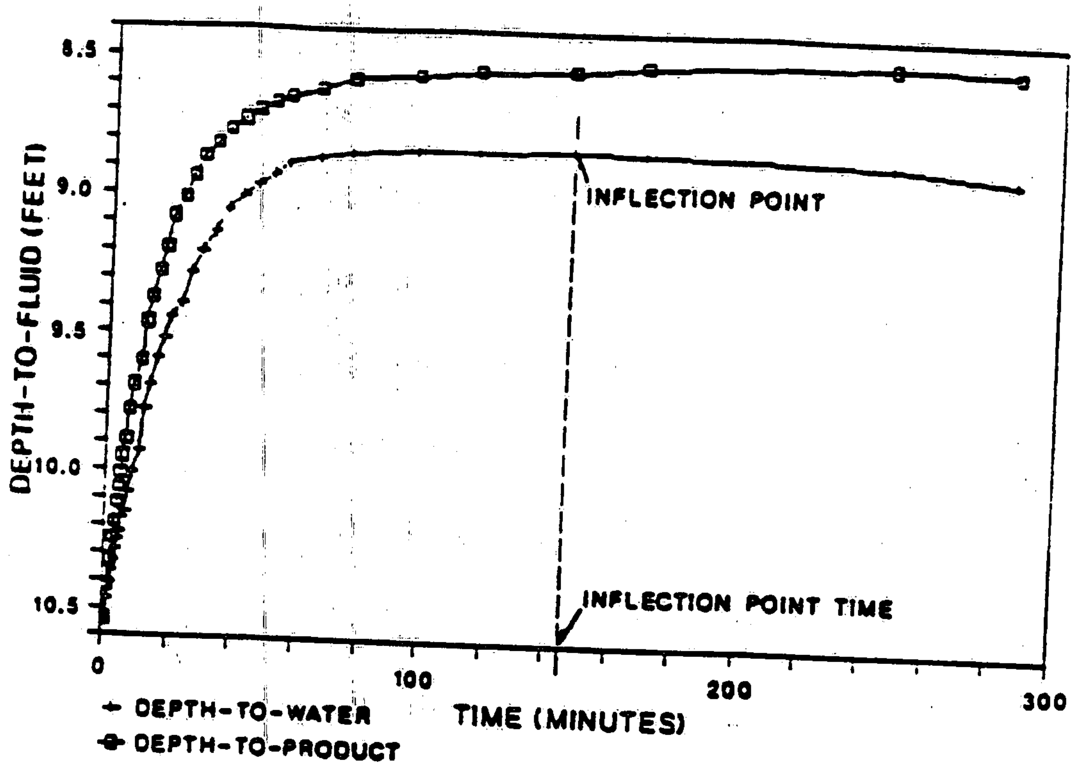


Figure 1 Apparent Hydrocarbon Thickness in a Well and Adjacent Formation



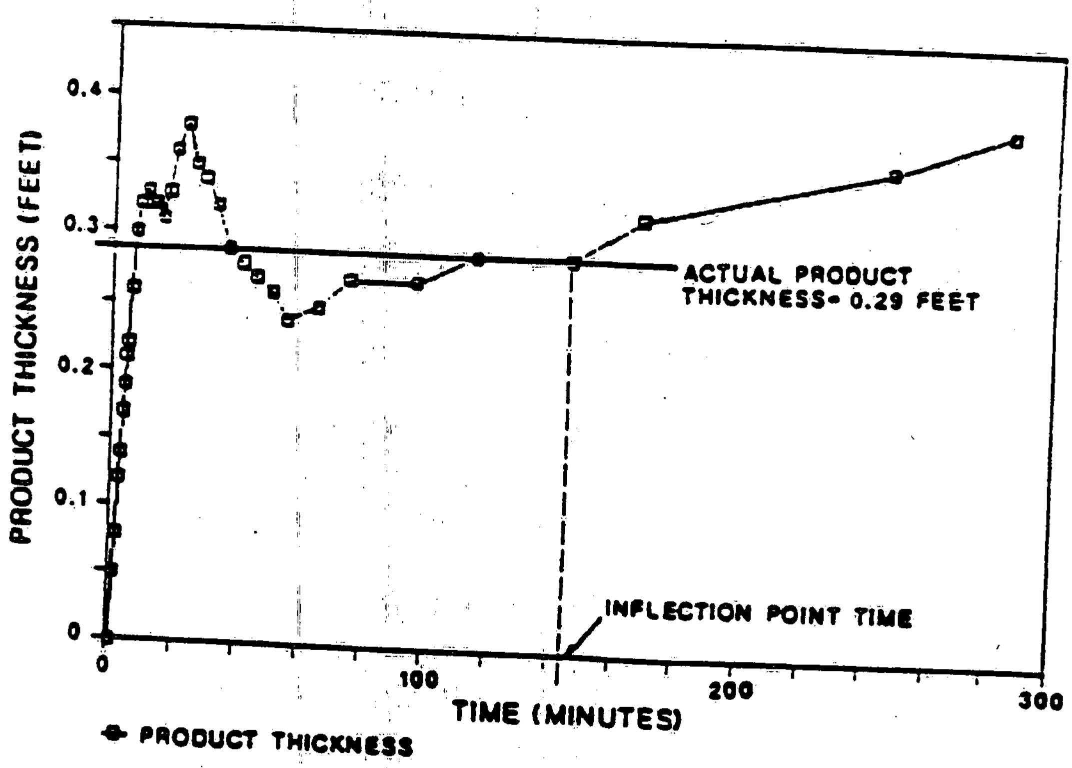


Figure 2 Representative Bail-Down Testing Curve Results

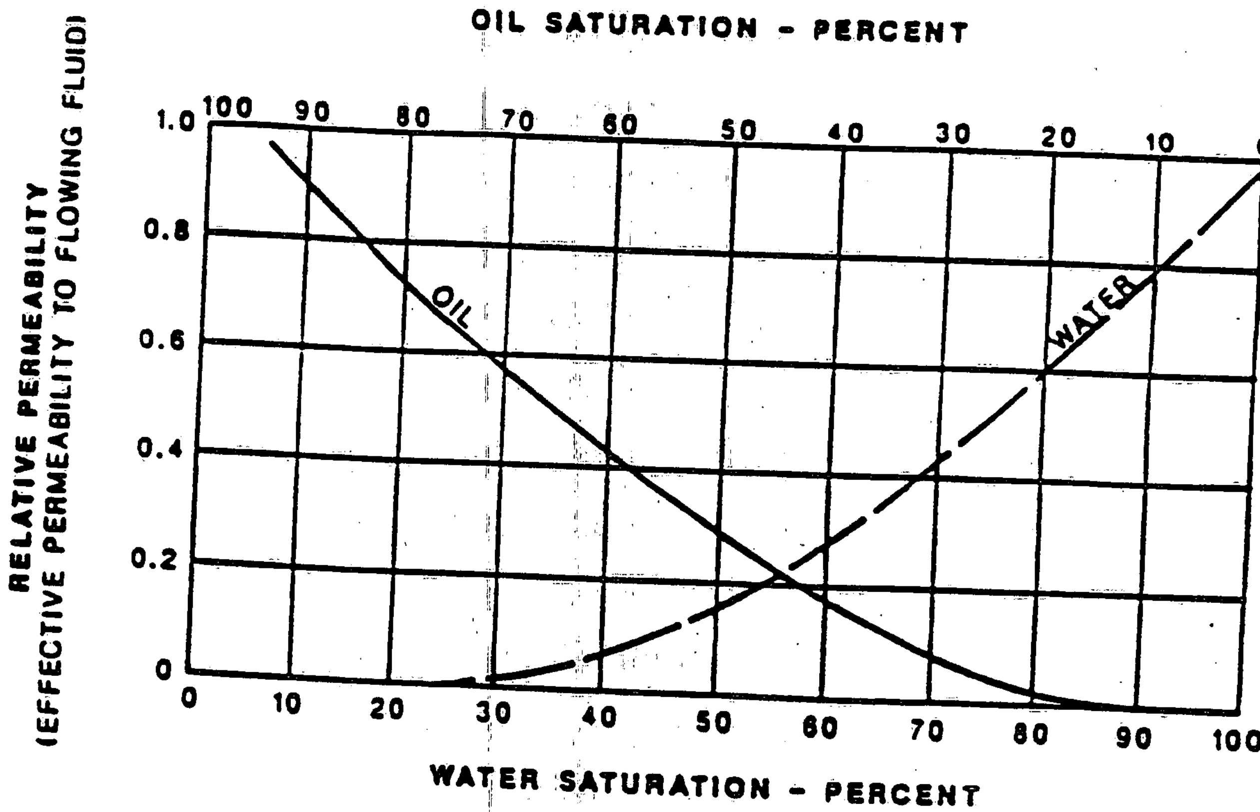


Figure 3 Relative Permeability Curves for Oil and Water (after Lavorsen, 1967)